APPENDIX B

ENGINE EXHAUST TEMPERATURE STUDY

I. Introduction

The passive diesel particulate filter (DPF) is the only diesel emission control strategy verified to achieve greater than 85 percent diesel particulate matter (PM) as of March 2003. As this is the best available diesel emission retrofit control technology for collection vehicles to comply with the proposed regulation, this study was conducted to evaluate the applicability of passive DPFs to various types of solid waste collection vehicles through the measurement of engine exhaust temperature. The purpose of this study was to determine which collection vehicle duty cycles would be able to use passive DPF to reduce diesel PM emissions by 85 percent or greater. Secondarily, staff can use the results to evaluate the feasibility of a newer technology, a flow through filter (FTF), based on its projected requirements for a minimum engine exhaust temperature. Diesel oxidation catalysts (DOC) are not dependent on engine exhaust temperature for successful and efficient operation, thus the results of this study do not apply to DOCs.

The success of a passive DPF relies on four main components: NOx to PM ratio, total PM emissions, vehicle space availability for the passive DPF, and engine exhaust temperature. Post-1991 heavy-duty diesel engines are best for achieving the NOx to PM ratio. The maximum PM emissions the passive DPF can handle are predicated, in part, by the frequency of filter regeneration, which, in turn, is dictated by the engine exhaust temperature profile. Johnson Matthey's verified CRT (CRT) requires engine exhaust temperatures of 260 degrees Celsius for at least 40 percent of the duty cycle (ARB 2002a). Engelhard's verified DPX (DPX) requires an average of 225 degrees Celsius engine exhaust temperature with temperatures in excess of 300 degrees Celsius for a minimum of ten percent of the duty cycle (ARB 2002b).

A study by Engine, Fuel and Emission Engineering on Waste Management vehicles that found four out of five of collection vehicles could not meet the CRT regeneration temperature requirements (ARB 2002a; Stoddard, 2001), prompted ARB staff to question what percentage of California's collection vehicle fleet might be able to achieve sufficient engine exhaust temperatures. Since the proposed regulation would apply to front, side and rear loader collection vehicles as well as roll offs in California, ARB staff exhaust temperature datalogged 60 collection vehicles distributed across the vehicle types.

The four main types of collection vehicles used to collect solid waste are automated side loaders, front loaders, rear loaders, and roll offs. Automated side loaders experience an intense stop-and-go duty cycle, as these are typically the collection vehicles that service residential homes. Front loaders are used to collect bins from commercial facilities, apartment complexes, or in special circumstances. These vehicles can have significant idle time while the bin in moved out for dumping. Rear loaders historically serviced residential areas with a stop-and-go duty cycle at each home, but are now often used primarily for bulk item collection. Roll offs are used in construction and bulk pick-up situations where a large bin is required for a time. The collection vehicle can only carry one bin at a time, and, therefore, experiences the duty cycle that has the least stop-and-go activity.

I. Methodology

The study was conducted from December 2001 to December 2002. Engine exhaust temperatures were measured from 60 vehicles in six collection vehicle fleets (three public, two private) based on a number of duty cycle variables: vehicle type (front, side, rear loader or roll off), engine model year and make. Staff correlated engine exhaust temperatures to these parameters and determined which percentage of the fleet might be able to use passive DPF successfully. In addition to engine exhaust temperature, load, speed, and location second-by-second data were collected for a number of the collection vehicles. Correlations between these additional parameters and engine exhaust temperature will be analyzed in a later document.

A. Vehicle Selection

ARB staff chose six representative fleets with a cross section of collection vehicles types. To capture the percentage of the fleet that can use passive DPFs, ARB staff acquired exhaust temperature data for 60 collection vehicles (Table 1) between January 2002 and January 2003. Four vehicles were measured again in March 2003 to verify captured data.

Table 1. Tested Collection Vehicles Profiles

		Engine		
Vehicle Type	Number	Model Year	Manufacturer	Model
Front End Loader	1	1985	Navistar	DT 466
Front End Loader	1	1987	Cummins	L10
Front End Loader	3	1989	Cummins	L10
Front End Loader	5	1990	Cummins	L10
Front End Loader	1	1991	Caterpillar	3208
Front End Loader	1	1991	Cummins	L10
Front End Loader	2	1992	Cummins	L10
Front End Loader	1	1996	Volvo	D7
Front End Loader	1	1999	Volvo	D7
Rear Loader	6	1999	Caterpillar	3126
Rear Loader	3	2000	Cummins	ISC 8.3
Rear Loader	4	2001	Cummins	ISC 8.3
Roll off	1	1980	DDC	671 TA
Roll off	1	1988	Cummins	NTC-365
Roll off	1	1990	Cummins	C8.3

Roll off	1	1991	Cummins	C8.3
Roll off	1	1991	Cummins	NTC-350
Roll off	1	1992	Caterpillar	3406-B
Roll off	1	1993	Cummins	L10
Roll off	1	1994	Cummins	C8.3
Roll off	1	1995	Cummins	C8.3
Roll off	1	1996	Cummins	C8.3
Side Loader	1	1987	Cummins	L10
Side Loader	1	1989	Cummins	L10
Side Loader	3	1994	Cummins	L10
Side Loader	1	1997	Cummins	M11
Side Loader	4	1998	Cummins	M11
Side Loader	3	1999	Cummins	ISM
Side Loader	1	1999	Cummins	M11
Side Loader	2	2000	Caterpillar	C10
Side Loader	2	2001	Cummins	ISC
Small Side Loader	3	2000	Caterpillar	3126
Total	60			

B. Equipment

1. Engine Exhaust Temperature Dataloggers

The exhaust temperature dataloggers were four DT500 Series DataTakers purchased by the ARB in 2001. They collect engine exhaust temperature and rotations per minute (rpm; engine load) on a second-by-second basis, but can change to another interval if required (DataTaker, no date).

2. Hertz Sensors

Sensors to register hertz were coupled with the engine exhaust temperature dataloggers. The data from these sensors were converted to rotations per minute (rpm) by multiplying the hertz by 60 and dividing by the number of teeth on the flywheel, which was 103 for all of the engines.

3. GPS Dataloggers

Four Nav Master Track Master GPS Data Recorders purchased by the ARB in 1999 were used to record latitude, longitude, and vehicle speed. The GPS recorder has an eight-megabyte memory, a magnetic GPS antenna, a lockable metal box, two sealed 12-volt lead-acid batteries, and a power harness with an added cigarette lighter adapter. The dimensions were small (2” by 6.75” by 7”) enough to fit in the box that held the exhaust temperature datalogger. The GPS dataloggers collected data on a second-by-second basis.

C. Fleet Composition

ARB staff recorded basic information on each collection vehicle on the data collection sheet (Figure 1). Staff installed dataloggers on the 60 collection vehicles. The collection vehicles were representative of the vehicle types and engine makes (Tables 2 and 5). Front, side and rear loaders and rolloffs, were all represented in the datalogging. Also, all of the engines found in California's collection vehicle fleet were represented, except for Mack engines, which comprised only two percent of California's collection vehicle fleet as calculated from ARB's DRIED 2001 database (Appendix C).

ARB collected data from vehicle from six fleets – three government-owned: City of Los Angeles – Sanitation Department, City of Pasadena, City of Long Beach, and three privately-owned: CR&R, Big Bear City Community Services, and Waste Management. These fleets represented the variety of inclines these collection vehicles might experience in distinct geographic areas from high altitude to coast to desert. The data were collected for a minimum of one week (5 days) on each vehicle with approximately 100,000 seconds worth of data for each parameter (exhaust temperature, rpm, and speed).

Table 2. Tested Fleet versus California's Collection Vehicle Fleet Composition

	Air Resources Board Test Fleet		California's Collection Vehicle Fleet
Factor	**No. Vehicles**	**Percentage**	**Percentage**
Cummins	43	72%	65%
Caterpillar	13	22%	12%
DDC	1	2%	2%
Mack	0	0%	2%
Navistar	1	2%	7%
Volvo	2	3%	13%
TOTAL:	60	100%	100%
SL	21	35%	37%
FL	16	27%	27%
RL	13	22%	28%
Roll off	10	17%	8%
TOTAL:	60	100%	100%
1994-2002	37	62%	43%
1991-1993	8	13%	17%
1988-1990	11	18%	18%
1970-1987	4	7%	22%
TOTAL:	60	100%	100%

Figure 1. Vehicle Data Collection Sheet

CONTACT INFORMATION	Date:	Init:

1. Fleet Contact Name:				
2. Fleet Business Name:				
3. Fleet Terminal #:				
4. Fleet Terminal Address:				
VEHICLE INFORMATION				
5. Vehicle Identification No.:				
6. License Plate No.:			Comments:	
7. Vehicle Type/Model:				
8. Vehicle Manufacturer:				
9. Vehicle GVWR:		Pounds		
10. Vehicle Model Year:				
11. Estimated mpg:		mpg		
12. Current Vehicle Mileage:		Miles		
ENGINE INFORMATION				
13. Engine Manufacturer:				
14. Engine Model:				
15. Engine Model Year:				
16. Engine Horsepower:				hp
17. Engine Displacement:				in^3/liters
18. Current Engine Mileage:				miles/hours
19. Engine Mileage at Last Rebuild, Repower, Replacement:				miles/hours
20. Engine Mileage when Next Expect to Rebuild Engine:				miles/hours
21. Fuel Injection:			Yes/No	
22. Aspiration:			Yes/No	
23. Transmission:				
24. Cycle			Two/four	
25. Fuel Sulfur Content:			CARB/15 ppm	
26. Number of teeth on the flywheel:				
27. Emission Certification:				
EXHAUST INFORMATION				
28. Exhaust Location:			Up/down	
29. Exhaust Configuration:			Single/dual	
30. Exhaust Pipe Diameter:				mm/inches
31. Underbody Clearance:				inches
32. Currently using DPF?			Yes/No	
OIL CONSUMPTION INFORMATION				
33. Current Engine Lubricating Oil Consumption				Qts/Wk
34. What is manufacturer's suggested oil consumption?				______/______
35. Does engine utilize devices that enable less frequent oil changes?			Yes/No	
36. How often is crankcase oil replaced with new oil?				______/______
FUEL DATA				
37. Where do you buy your diesel fuel?				
38. How frequently do you buy your fuel?				per
39. How much do you buy each time?				Gallons
ARB DATA COLLECTION				
40. Smoke opacity test results (attach results strip to this sheet)			1:	4:
			2:	5:
			3:	6:
40. Does the vehicle have access to power source for active DPF?			YES/NO What:	

II. Results and Discussion

A. Engine Exhaust Temperatures

Engine exhaust temperatures were collected and analyzed for the applicability of one of two passive DPFs or one type of FTF, for which ARB has data on required minimum engine exhaust temperatures. A greater percentage of the collection vehicles were able to meet the engine exhaust temperature requirements of the FTF than either passive DPF.

1. Passive Diesel Particulate Filters

In general, the collection vehicles experienced low engine exhaust temperatures. The CRT requirements were met by 35 percent of the tested vehicles, whereas the DPX requirements were met by 48 percent of the test vehicles.

a. Analysis By Vehicle Type

The results analyzed by vehicle type illustrate which collection vehicle duty cycles appear to be more difficult than others. In all cases, relative to the CRT, the DPX engine exhaust temperature requirements were easier to meet, or were equally met as in the case of roll offs. Side and front end loaders had duty cycles most amenable to the use of these passive DPFs (Figure 2), with approximately 70 percent achieving the Engelhard regeneration temperatures and 50 percent achieving Johnson Matthey CRT regeneration temperatures for both. Rear loaders and roll offs experienced little success with only one or two vehicles achieving the appropriate regeneration temperatures.

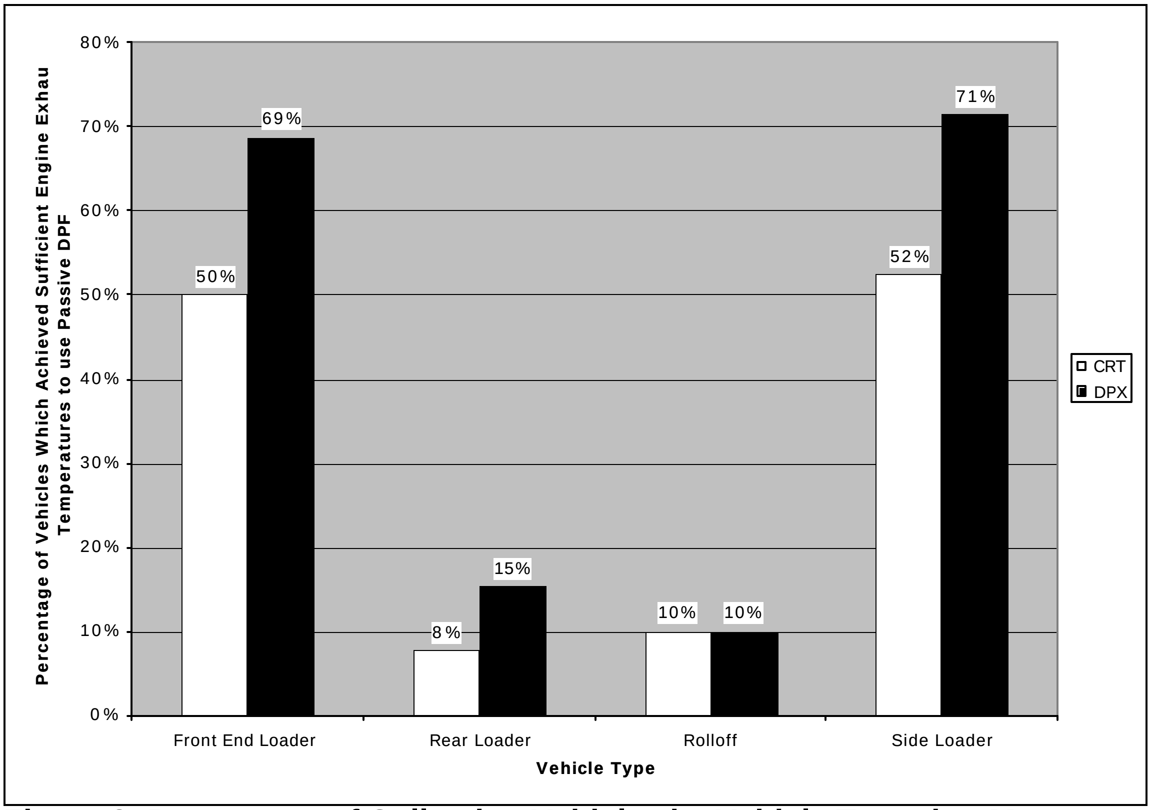

Figure 2. Percentage of Collection Vehicles by Vehicle Type that Met Engine Exhaust Temperature Requirements for Two Variations of Passive Diesel Particulate Filters.

b. Analysis By Engine Type

Cummins and Caterpillar engines comprise the greatest percent of test collection vehicles. Out of 60 vehicles tested, 56 had Cummins or Caterpillar engines. Of the Caterpillar engines, 23 or 31 percent achieved the CRT or DPX engine exhaust temperature requirements, respectively (Table 3). A greater percentage of the Cummins engines achieved the engine exhaust temperature requirements with 37 or 51 percent achieving the CRT or DPX engine exhaust temperature requirements, respectively (Table 3).

Table 3. Percentage of Collection Vehicles by Engine Make that Met Engine Exhaust Temperature Requirements for Two Variations of Passive Diesel Particulate Filters.

Engine Manufacturer	n	Achieved Exhaust Temperature Requirement CRT	DPX
Caterpillar	13	23%	31%
Cummins	43	37%	51%
DDC	1	0%	0%
Navistar	1	100%	100%
Volvo	2	50%	100%
Total	60	35%	48%

c. Analysis By Model Year

The data indicate a difference in exhaust temperature by model year (Table 4), but staff believes this may be an artifact attributed to the vehicle type more than the model year. For example, of the 1988 to 1990 vehicles tested, all of the vehicles that achieved the engine exhaust temperature requirements were front loaders (Table 5).

Table 4. Number of Collection Vehicles by Engine Model Year that Met Engine Exhaust Temperature Requirements for Two Variations of Passive Diesel Particulate Filters.

Engine Model Year	n	Achieved Exhaust Temperature Requirement CRT	DPX
Pre-1988	4	25%	25%
1988-1990	11	73%	82%
1991-1993	8	0%	13%
1994-2002	37	32%	49%

Table 5. Matrix of Test Collection Vehicle Engines and Ability to Achieve Engine Exhaust Temperature Requirements of Two Passive DPF and one FTF.

ID	Vehicle Type	Engine Model Year	Engine Manufacturer	Engine Model	Achieved Engine Exhaust Temperature Requirement FTF	CRT	DPX
1	Front End Loader	1991	Caterpillar	3208	YES	NO	NO
2	Rear Loader	1999	Caterpillar	3126	YES	NO	NO
3	Rear Loader	1999	Caterpillar	3126	YES	NO	NO
4	Rear Loader	1999	Caterpillar	3126	YES	NO	NO
5	Rear Loader	1999	Caterpillar	3126	YES	NO	NO
6	Rear Loader	1999	Caterpillar	3126	NO	NO	NO
7	Rear Loader	1999	Caterpillar	3126	NO	NO	NO
8	Rolloff	1992	Caterpillar	3406-B	NO	NO	NO
9	Side Loader	2000	Caterpillar	C10	YES	NO	NO
10	Small Side Loader	2000	Caterpillar	3126	YES	NO	YES

11	Side Loader	2000	Caterpillar	C10	YES	YES	YES
12	Small Side Loader	2000	Caterpillar	3126	YES	YES	YES
13	Small Side Loader	2000	Caterpillar	3126	YES	YES	YES
14	Front End Loader	1987	Cummins	L10	YES	NO	NO
15	Front End Loader	1990	Cummins	L10	YES	NO	NO
16	Front End Loader	1990	Cummins	L10	YES	NO	YES
17	Front End Loader	1991	Cummins	L10	YES	NO	YES
18	Front End Loader	1992	Cummins	L10	YES	NO	NO
19	Front End Loader	1992	Cummins	L10	YES	NO	NO
20	Rear Loader	2000	Cummins	ISC 8.3	YES	NO	NO
21	Rear Loader	2000	Cummins	ISC 8.3	NO	NO	NO
22	Rear Loader	2000	Cummins	ISC 8.3	NO	NO	NO
23	Rear Loader	2001	Cummins	ISC 8.3	YES	NO	NO
24	Rear Loader	2001	Cummins	ISC 8.3	NO	NO	NO
25	Rear Loader	2001	Cummins	ISC 8.3	YES	NO	YES
26	Rolloff	1988	Cummins	NTC-365	NO	NO	NO
27	Rolloff	1991	Cummins	C8.3	NO	NO	NO
28	Rolloff	1991	Cummins	NTC-350	YES	NO	NO
29	Rolloff	1993	Cummins	L10	YES	NO	NO
30	Rolloff	1994	Cummins	C8.3	NO	NO	NO
31	Rolloff	1995	Cummins	C8.3	NO	NO	NO
32	Rolloff	1996	Cummins	C8.3	NO	NO	NO
33	Side Loader	1987	Cummins	L10	NO	NO	NO
34	Side Loader	1994	Cummins	L10	YES	NO	YES
35	Side Loader	1994	Cummins	L10	YES	NO	YES
36	Side Loader	1997	Cummins	M11	YES	NO	NO
37	Side Loader	1998	Cummins	M11	YES	NO	NO
38	Side Loader	1999	Cummins	ISM	YES	NO	NO
39	Side Loader	1999	Cummins	M11	YES	NO	NO
40	Side Loader	2001	Cummins	ISC	YES	NO	YES
41	Front End Loader	1989	Cummins	L10	YES	YES	YES
42	Front End Loader	1989	Cummins	L10	YES	YES	YES
43	Front End Loader	1989	Cummins	L10	YES	YES	YES
44	Front End Loader	1990	Cummins	L10	YES	YES	YES
45	Front End Loader	1990	Cummins	L10	YES	YES	YES
46	Front End Loader	1990	Cummins	L10	YES	YES	YES
47	Rear Loader	2001	Cummins	ISC 8.3	YES	YES	YES
48	Rolloff	1990	Cummins	C8.3	YES	YES	YES
49	Side Loader	1989	Cummins	L10	YES	YES	YES
50	Side Loader	1994	Cummins	L10	YES	YES	YES
51	Side Loader	1998	Cummins	M11	YES	YES	YES
52	Side Loader	1998	Cummins	M11	YES	YES	YES
53	Side Loader	1998	Cummins	M11	YES	YES	YES
54	Side Loader	1999	Cummins	ISM	YES	YES	YES
55	Side Loader	1999	Cummins	ISM	YES	YES	YES
56	Side Loader	2001	Cummins	ISC	YES	YES	YES
57	Rolloff	1980	DDC	671 TA	YES	NO	NO
58	Front End Loader	1985	Navistar	DT 466	YES	YES	YES

59	Front End Loader	1996	Volvo	D7	YES	NO	YES
60	Front End Loader	1999	Volvo	D7	YES	YES	YES

2. Engine Exhaust Temperatures for Flow Though Filters

While no published literature exists on FTF engine exhaust temperature requirements, Johnson-Matthey representatives have suggested an engine exhaust temperature requirement at or above 200 degrees Celsius for 50 percent of the duty cycle as a guideline for a planned demonstration. Analyzing the data for this temperature guideline, staff determined that 48 out of 60 vehicles, or 80 percent, met this requirement. By vehicle type, 100 percent of front loaders, 62 percent of rear loaders, 40 percent of roll offs, and 95 percent of side loaders met this requirement. All of the engine model year groups met this requirement by 75 percent or more.

B. Implications for Solid Waste Collection Vehicle Fleet Retrofit Feasibility

The results suggest that DPFs may not be able to be used on the full number of collection vehicles in the verified engine families (see Diesel Emission Control Strategies for In-Use Engines) without significant assistance in increasing the engine exhaust temperature through greater catalysis or locating the DPF closer to the engine. For the FTF technology, the data indicate that this technology may be feasible for a much higher percentage of vehicles, as high as 80 percent. Front and side loaders appear to be most suitable to application of either the passive DPF or FTF, although a substantial percentage of rear loaders and roll offs may also find this technology to be feasible.

ARB will investigate further the source of engine exhaust temperature variability. The prediction is the duty cycles vary in terrain, or engine load, vehicle speed and distance. In addition, there are potential sources of error in the data, which will be further analyzed and reported.

III. References

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